Mechanisms for Spatially Inhomogeneous Changes in East Asian Summer Monsoon Precipitation during the Mid-Holocene

NA WANG

Institute of Atmospheric Physics, Chinese Academy of Sciences, and University of Chinese Academy of Sciences, Beijing, China

DABANG JIANG

Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, and Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science and Technology, Nanjing, and CAS Center for Excellence in Tibetan Plateau Earth Sciences, and University of Chinese Academy of Sciences, Beijing, China

XIANMEI LANG

Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, and Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science and Technology, Nanjing, and CAS Center for Excellence in Tibetan Plateau Earth Sciences, Beijing, China

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ABSTRACT

The East Asian summer monsoon (EASM) intensified during the early to mid-Holocene relative to the present primarily due to orbital forcing. However, on the regional scale, changes in the monsoonal precipitation exhibit considerable spatial disparity, and the underlying mechanisms remain unresolved. In this study, the dynamic processes responsible for the difference of the EASM precipitation between the mid-Holocene and preindustrial period are systematically examined using the CMIP5 multimodel simulations. The moisture budget diagnostic identifies vertical motion as the key factor determining the cross-like precipitation pattern in East Asia. Relative to the preindustrial period, the mid-Holocene anomalous ascending motion corresponds well with the excessive precipitation over northern and southern China, and vice versa for west-central China, the Korean peninsula, Japan, and its marginal seas. In the framework of the moist static energy budget, the increased insolation and the attendant intensification of land–sea thermal contrast give rise to anomalous ascending motions, while descending motions are fundamentally forced by the decreased latitudinal insolation gradient. In particular, thermodynamic changes, namely, the reduced pole–equator temperature and humidity gradients, account for the downward motions over the northwestern Pacific. Dynamic changes, namely, the weakened westerlies, play a leading role in suppressing updrafts in west-central China. This study highlights that the orbital-scale monsoonal precipitation changes are not solely determined by local radiative forcing as repeatedly emphasized before. The latitudinal uneven distribution of insolation is crucial to explain the spatial inhomogeneity in the EASM precipitation changes during the Holocene.

1. Introduction

The East Asian summer monsoon (EASM) is a key component of the global monsoon system, influencing nearly one-fifth of the world's population living in

eastern China, the Korean peninsula, and Japan. Precipitation variability associated with the EASM has profound implications on the local ecosystem, agriculture, and society through its modulation on the available water resource (Huang et al. 2007), and thus has attracted great attention in the field of climate change (e.g., Ding 2007; Gao et al. 2008; Chen et al. 2015). Despite much progress, it is still challenging to project future EASM precipitation changes based on our knowledge from the instrumental observations only spanning the past few decades (Kang et al. 2002; Sperber et al. 2013). The geological data record climatic evolution in

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Corresponding authors: Dabang Jiang, jiangdb@mail.iap.ac.cn; Xianmei Lang, langxm@mail.iap.ac.cn

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Earth's history provides a unique opportunity for understanding the response of the EASM to various forcings and potentially for improving the models' reliability in future climate projection (Braconnot et al. 2012; Mohtadi et al. 2016).

In East Asia, the summer monsoonal rainfall occupies more than half of the total precipitation throughout the year (Ding and Chan 2005; Sui et al. 2013). The precipitation-sensitive proxies reconstructed from lake sediments (e.g., Chen et al. 2006; Zhou et al. 2016), loess sequences (e.g., Huang et al. 2009; Lu et al. 2013), speleothem records (e.g., Dykoski et al. 2005; Cosford et al. 2008; Dong et al. 2010), and other sources (e.g., Wang et al. 2010; Zheng et al. 2018) have been extensively used in the studies of the paleo-EASM. Most of the reconstructions agree on the intensified EASM at the early to mid-Holocene (10–4 ka) relative to the present (Ran and Feng 2013; Jin et al. 2014; Wang et al. 2017). However, the timing and duration of the maximum monsoonal rainfall corresponding to the Holocene moisture optimum have long been controversial across regions. One view argues that the peak precipitation appeared at the early Holocene (10–6 ka), and then gradually declined to the present level, as suggested by the speleothem records in southern China (Dykoski et al. 2005; Dong et al. 2010; Jiang et al. 2012), as well as some lake records in northern China (Jiang et al. 2006; Goldsmith et al. 2017). By contrast, other evidence in northern and central China indicates that the monsoonal rainfall did not reach its maximum until the mid-Holocene (8–3 ka) (Chen et al. 2015; Liu et al. 2015; Wen et al. 2017). Based on the synthesis of multiproxy records, An et al. (2000) proposed a time-transgressive hypothesis that the peak precipitation gradually shifted southeastward from north-central China in the early Holocene (10–7 ka) to southern China in the late Holocene (3 ka), in response to the progressively reduced summer insolation. However, recent vegetation reconstructions display an opposite northward migration of the Holocene optimum, with a postponed optimum at the higher latitudes (Zhou et al. 2016). There are also studies in support of the synchronous Holocene moisture changes, such as Zhao et al. (2009), who suggested that the humid climate occurred nearly contemporaneously between 9.5 and 6 ka in different regions of monsoonal China, and Herzschuh (2006), who proposed a spatially uniform reduction of effective moisture in monsoonal central Asia after 3 ka. The above controversies call for a better explanation of the well-dated and high-resolution sequences in the future studies (Ran and Feng 2013). On the other hand, an in-depth understanding of the regional-scale monsoon precipitation dynamics from the perspective of numerical simulation is highly needed.

Previous numerical studies consistently suggested that summer insolation dominates the weakening of the EASM from the early to mid-Holocene toward the present (Liu et al. 2003; Jiang et al. 2013, 2015; Zheng et al. 2013). Recently, attention has been turned on the nature and cause of spatial differences in the EASM precipitation. According to the TraCE-21 ka transient simulation (Liu et al. 2009), the trend of the Holocene EASM precipitation in southern China (28°–38°N, 112°–124°E) matches with that of the boreal summer solar radiation, while the maximum precipitation in arid/semiarid northern China (38°–53°N, 80°–105°E) lags peak insolation by 2–3 ka (Lu et al. 2019). By comparing the full and single forcing experiments, Lu et al. (2019) argued that the remnant ice sheet in the early Holocene suppressed the summer rainfall in northern China but had little effect on the south, eventually leading to the meridional asynchronous evolution of precipitation. They also attributed the droughts of northern China and floods of southern China during the late Holocene to the influence of internal air–sea feedback associated with El Niño–Southern Oscillation (ENSO). Another Holocene transient simulation conducted by the Kiel Climate Model (KCM) similarly shows that the ENSO variability is highly correlated with the antiphasing evolution of the northern and southern monsoonal rainfall (Jin et al. 2014). Note that the above northern and southern monsoonal rainfall refers to rainfall that occurred in regions within 30°–40°N and 20°–30°N in East Asia (100°–120°E), which should be distinguished from the rainfall over northern and southern China in Lu et al. (2019). In addition to the latitudinal discrepancy, Zhang et al. (2018) recently found the summer precipitation minimum appeared at the early to mid-Holocene in eastern Northeast Asia but at the late Holocene in western Northeast Asia. Their study indicated that the east–west contrast is due to the interaction of the monsoon circulation, westerlies, and northwestern Pacific subtropical high under the constraints of orbital forcing.

Changes in the total amount of precipitation relate to not only the precipitation intensity but also the duration of rainfall seasons. The seasonal evolution of the EASM involves the meridional shifts of the rainfall belt, which is characterized by the two abrupt jumps between the three quasi-stationary stages (Ding and Chan 2005). Furthermore, the two jumps are in conjunction with the stepwise northward shifts of the westerly jet (Schiemann et al. 2009). On this basis, Chiang et al. (2015) proposed a jet transition hypothesis that changes in the meridional position of the westerlies modulate the onset and duration of rainfall seasons in different parts of the monsoon regions, which play an important role in the evolution of paleoclimate in East Asia. Following this hypothesis,

TABLE 1. Basic information about the 14 CMIP5 models used in this study (PI and MH denote the preindustrial and mid-Holocene, respectively).

Model	Country	Atmospheric resolution	Ensemble member (PI/MH)	References
BCC_CSM1.1	China	$\sim 2.8^\circ \times \sim 2.8^\circ$, L26	r1i1p1/r1i1p1	Wu et al. (2013)
CCSM4	United States	$\sim 1.3^\circ \times \sim 0.9^\circ$, L26	r1i1p1/r1i1p1	Gent et al. (2011)
CNRM-CM5	France	$\sim 1.4^\circ \times \sim 1.4^\circ$, L31	r1i1p1/r1i1p1	Voldoire et al. (2013)
CSIRO Mk3.6.0	Australia	$\sim 1.9^\circ \times \sim 1.9^\circ$, L18	r1i1p1/r1i1p1	Rotstayn et al. (2010)
CSIRO Mk3L-1.2	Australia	$\sim 5.6^\circ \times \sim 3.2^\circ$, L18	r1i1p1/r1i1p1	Phipps et al. (2011)
FGOALS-g2	China	$\sim 2.8^\circ \times \sim 2.8^\circ$, L26	r1i1p1/r1i1p1	Li et al. (2013)
FGOALS-s2	China	$\sim 2.8^\circ \times \sim 1.7^\circ$, L26	r1i1p1/r1i1p1	Bao et al. (2013)
GISS-E2-R	United States	$2.5^\circ \times 2^\circ$, L40	r1i1p142/r1i1p1	Schmidt et al. (2006)
HadGEM2-CC	United Kingdom	$\sim 1.9^\circ \times \sim 1.3^\circ$, L60	r1i1p1/r1i1p1	Collins et al. (2011)
HadGEM2-ES	United Kingdom	$\sim 1.9^\circ \times \sim 1.3^\circ$, L38	r1i1p1/r1i1p1	Collins et al. (2011)
IPSL-CM5A-LR	France	$\sim 3.8^\circ \times \sim 1.9^\circ$, L39	r1i1p1/r1i1p1	Dufresne et al. (2013)
MIROC-ESM	Japan	$\sim 2.8^\circ \times \sim 2.8^\circ$, L80	r1i1p1/r1i1p1	Watanabe et al. (2011)
MPI-ESM-P	Germany	$\sim 1.9^\circ \times \sim 1.9^\circ$, L47	r1i1p1/r1i1p1	Raddatz et al. (2007)
MRI-CGCM3	Japan	$\sim 1.1^\circ \times \sim 1.1^\circ$, L48	r1i1p1/r1i1p1	Yukimoto et al. (2011)

Kong et al. (2017) investigated the seasonal transition of the EASM during the Holocene. In their study, the northward-shifted westerlies at the early to mid-Holocene give rise to the earlier onset of mei-yu and midsummer stages to varying degrees, and ultimately shorten the mei-yu and prolong the midsummer rainfall season in comparison with the late Holocene. Such results agree with the later appearance of the Holocene precipitation maximum in the southern monsoonal regions as proposed by An et al. (2000).

Altogether, the existing paleoclimate proxy records and model simulations reveal the complexity in the spatiotemporal variation of the Holocene EASM. Possible mechanisms related to changes in the external forcings and internal air–sea feedbacks have been proposed for the spatial disparity in the monsoon precipitation changes. Even so, the causes of the regional-scale precipitation changes during the Holocene and the relative contributions from different physical processes remain poorly understood. To address the above questions, we use the multimodel simulations from phase 5 of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012) to examine the specific and robust dynamics that determine the precipitation difference between the mid-Holocene (6 ka) and preindustrial (0 ka, as reference) period. Using the moisture and moist static energy (MSE) budget, we attempt to find the key factors influencing local precipitation changes and their connections to the altered orbital forcing.

This paper is organized as follows. Section 2 briefly describes the data and methods used in this study.

Section 3 shows the modern climatology of the EASM precipitation as well as an assessment of the models' performance. Section 4 presents the mid-Holocene precipitation changes relative to the preindustrial, while the relevant dynamic interpretation is given in section 5. Finally, a summary and discussion are provided in section 6.

2. Data and methods

a. CMIP5 models and observational dataset

Model data used in this study mainly come from the monthly single realization outputs archived in the CMIP5 mid-Holocene and preindustrial experiments. A total of 14 climate models are available for precipitation analysis, and more information about these models is provided in Table 1. For each model, the two sets of equilibrium experiments are constrained by the boundary conditions consistent with the coordinated CMIP5 protocol (Taylor et al. 2012). Apart from orbital parameters and atmospheric CH_4 concentration, the boundary conditions for the mid-Holocene experiment are the same as those for the preindustrial (see Table 2). Here, we only focus on the precipitation changes during the summer season spanning from June to August (JJA). The last 30 years of each simulation are averaged to represent their climatology. Besides, monthly precipitation data from the Global Precipitation Climatology Program (GPCP) for the period of 1979–2008 are used to evaluate

TABLE 2. Summary of the boundary conditions for the CMIP5 preindustrial and mid-Holocene experiments.

Period	Ice sheets	CO_2 (ppmv)	CH_4 (ppbv)	N_2O (ppbv)	Eccentricity	Obliquity ($^\circ$)	Angular precession ($^\circ$)
Preindustrial	Modern	280	760	270	0.016 772	23.446	102.04
Mid-Holocene	Modern	280	650	270	0.018 682	24.105	0.87

the models' performance (Adler et al. 2003). To make the model–observation comparison and obtain the multimodel mean (MMM), data with different horizontal resolutions are remapped on a common $0.5^\circ \times 0.5^\circ$ grid through bilinear interpolation.

b. Proxy records

The combination of model simulations and proxy records is conducive to a more comprehensive picture of past climate change. Moisture reconstructions that potentially reflect the mid-Holocene EASM precipitation changes relative to the present are collected for model–data comparison. Most of these reconstructions are derived from the synthetic review of Wang et al. (2010, 2017), with the rest coming from pertinent studies (e.g., Kramer et al. 2010; Zhou et al. 2016; Zhao et al. 2017; Zheng et al. 2018). Following Wang et al. (2010), the above reconstructions are further divided into six categories, and the main humidity proxies are shown in parentheses: lake (pollen, total organic content, and carbonate content), delta (pollen), loess (magnetic susceptibility), speleothem (oxygen isotope), profile (pollen, sediment description), and peat/mire/swamp (pollen, carbon isotopes of organic matter). Based on the contemporary correlation of proxies to humidity, in combination with the chronological measurement, the past moisture conditions are deduced from the reconstructed sequences. It should be noted that considerable uncertainties exist in the moisture reconstructions. One lies in the depth–age conversion, which makes it difficult to precisely identify the timing of the mid-Holocene. The nonequivalent relationship between proxies and monsoonal precipitation constitutes another kind of uncertainty. For example, the pollen-based records are influenced by multiple environmental factors such as seasonally dependent plant available moisture, temperature, and carbon dioxide concentration (Farrera et al. 1999; Bartlein et al. 2011). Lake-level status generally reflects the balance of precipitation, evaporation, and runoff, and for the high-altitude regions, the effect of snow melting should also be considered (Qin and Yu 1998). The interpretation of speleothem oxygen isotope remains controversial on whether it indicates changes in the summer rainfall or monsoon circulations (Dykoski et al. 2005; Cosford et al. 2008; Tan 2014). Thus, the moisture-related proxies provide evidence for past precipitation changes, but one caveat is that there are other signals mixed in. Given the uncertain nature of proxies, we only present the qualitative changes in the moisture conditions. More detailed information about these records can be found in the online supplemental material dataset S1 and the corresponding references therein.

c. Diagnostic methods

The equation for conservation of water vapor can be written as (Trenberth and Guillemot 1995)

$$\partial_t q + \mathbf{V} \cdot \nabla q + \omega \partial_p q = e - c, \quad (1)$$

where q is the specific humidity, $\mathbf{V}$ is the horizontal winds, ω is the vertical pressure velocity, and e and c are the evaporation and condensation rate per unit mass, respectively. The sum of terms on the left-hand side of the equation, namely, the material derivative of water vapor in unit mass of air equals the net rate of evaporation (source) minus condensation (sink) within. The mass-weighted vertical integral of Eq. (1) from the surface to the top of the atmosphere is expressed by

$$\langle \partial_t q \rangle + \langle \mathbf{V} \cdot \nabla q \rangle + \langle \omega \partial_p q \rangle = E - P, \quad (2)$$

where P is the precipitation and E is the evaporation at the surface; $\langle \cdot \rangle$ denotes the mass-weighted vertical integral [i.e., $(1/g) \int_0^{p_s} (\cdot) dp$, where g is the gravitational acceleration, and p_s is the surface pressure]. Note that the moisture equation present here is in its advection form, which could be converted into flux form using the equation of continuity (see the appendix for detailed derivation). These multiple forms of the moisture budget directly link precipitation to other relevant physical processes, and they have been widely used to investigate precipitation changes under different climate regimes (Seager et al. 2010; Chou and Lan 2012; Mantsis et al. 2013; Chen and Bordoni 2016). In this study, the tendency term $\langle \partial_t q \rangle$ is negligible for the climatological JJA mean. The horizontal and vertical moisture advection calculated from the monthly resolution data excludes contributions from the submonthly transient eddies. To close the equation, a residual term needs to be added. Equation (2) is then rewritten as

$$\bar{P} = -\langle \mathbf{V} \cdot \nabla q \rangle - \langle \omega \partial_p q \rangle + \bar{E} + \delta_q, \quad (3)$$

where $\bar{(\cdot)}$ indicates the climatological JJA mean, and δ_q denotes the residual term in the moisture budget mainly due to the transient eddies. Equation (3) is identical to Eq. (2) in Chou and Lan (2012).

Based upon the moisture budget analysis in section 5a, vertical velocity was identified as the key factor influencing the precipitation pattern in the EASM influenced regions. Thus, we use the MSE budget to further diagnose the physical processes associated with changes in the vertical velocity. As suggested by Chen and Bordoni (2014, 2016), the MSE budget characterizes the combined effects of temperature, humidity, and diabatic processes on circulation in a united theoretical framework. Thus, it

is a useful tool to understand the anomalous vertical motion in the tropical–subtropical monsoon regions where the role of water vapor cannot be ignored (Chou and Neelin 2003). Similar to Eq. (3), the climatological JJA mean MSE budget is expressed as

$$\overline{F^{\text{net}}} - \langle \overline{\mathbf{V} \cdot \nabla m_E} \rangle - \langle \overline{\omega \partial_p h} \rangle + \delta_E = 0, \quad (4)$$

and

$$F^{\text{net}} = S_t^\downarrow - S_t^\uparrow - S_s^\downarrow + S_s^\uparrow - L_t^\uparrow + L_s^\uparrow - L_s^\downarrow + \text{SH}^\uparrow + \text{LH}^\uparrow, \quad (5)$$

where F^{net} is the net energy flux into the atmospheric column, $m_E = c_p T + L_v q$ is the atmospheric moist enthalpy, $h = c_p T + gz + L_v q$ is the MSE, and δ_E is the residual term in the MSE budget. The net energy flux is balanced by the shortwave radiation (S), longwave radiation (L), sensible heat (SH), and latent heat (LH), with the subscripts t and s denoting the top of atmosphere and surface, respectively. Note that the MSE tendency has been omitted in Eq. (4), and see Chen and Bordoni (2014) for the original MSE budget and its derivation.

Changes in the horizontal and vertical advection in Eqs. (3) and (4) from the preindustrial period to the mid-Holocene can be further decomposed as follows (Seager et al. 2010; Chou and Lan 2012):

$$\begin{aligned} -\delta \langle \overline{\mathbf{V} \cdot \nabla Q} \rangle &\approx -\delta \langle \overline{\mathbf{V} \cdot \nabla Q} \rangle \approx -\langle \delta \overline{u} \partial_x \overline{Q} \rangle - \langle \overline{u} \delta \partial_x \overline{Q} \rangle \\ &\quad - \langle \delta \overline{u} \delta \partial_x \overline{Q} \rangle - \langle \delta \overline{v} \partial_y \overline{Q} \rangle - \langle \overline{v} \delta \partial_y \overline{Q} \rangle \\ &\quad - \langle \delta \overline{v} \delta \partial_y \overline{Q} \rangle, \end{aligned} \quad (6)$$

and

$$\begin{aligned} -\delta \langle \overline{\omega \partial_p Q} \rangle &\approx -\delta \langle \overline{\omega \partial_p Q} \rangle \approx -\langle \delta \overline{\omega} \partial_p \overline{Q} \rangle - \langle \overline{\omega} \delta \partial_p \overline{Q} \rangle \\ &\quad - \langle \delta \overline{\omega} \delta \partial_p \overline{Q} \rangle, \end{aligned} \quad (7)$$

where terms with δ indicate the mid-Holocene minus preindustrial, and terms without δ indicate the preindustrial. Approximations in Eqs. (6) and (7) consider that the transient eddies with a time scale larger than one month have a negligible contribution to the climatological average, and the calculation sequence of vertical integration and subtraction barely influence the final results. Here, Q denotes the temperature, specific humidity, or their combinations, which are regarded as the thermodynamic components. In each direction, changes in the total advection consist largely of changes due to dynamic (circulation) components ($-\langle \delta \overline{u} \partial_x \overline{Q} \rangle$, $-\langle \delta \overline{v} \partial_y \overline{Q} \rangle$, $-\langle \delta \overline{\omega} \partial_p \overline{Q} \rangle$),

changes due to thermodynamic components ($-\langle \overline{u} \delta \partial_x \overline{Q} \rangle$, $-\langle \overline{v} \delta \partial_y \overline{Q} \rangle$, $-\langle \overline{\omega} \delta \partial_p \overline{Q} \rangle$), and changes due to the covariance between them ($-\langle \delta \overline{u} \delta \partial_x \overline{Q} \rangle$, $-\langle \delta \overline{v} \delta \partial_y \overline{Q} \rangle$, $-\langle \delta \overline{\omega} \delta \partial_p \overline{Q} \rangle$).

3. Model evaluation

Figure 1 (left column) shows the modern climatology of summer precipitation in East Asia derived from the GPCP dataset. The EASM-related precipitation features unique monthly variations. In June, precipitation concentrates south of 35°N and features a southwest–northeast tilt distribution. The heaviest rainfall appears between 20° and 30°N in coastal eastern China and around 30°N over the northwestern Pacific. When it comes to July, rainfall belt moves northward as a whole and precipitation over northeastern China and the Korean Peninsula substantially increases. After that, the rainfall belt retreats to the south, with the weakened precipitation to the north of 30°N. For the JJA average, the maximum precipitation centers in southern China, the Korean peninsula, southern Japan, and its marginal seas.

Previous studies have suggested a considerable discrepancy in the EASM precipitation simulation among the CMIP5 models (e.g., Sperber et al. 2013; Huang et al. 2013). Thus, it is necessary to evaluate the performance of the 14 available models and select the qualified ones for further analysis (for the preindustrial EASM precipitation from each model, see Figs. S1–S4 in the online supplemental material). We use statistical quantities including the spatial correlation coefficient, the ratio of standard deviations, and the normalized centered root-mean-square (RMS) difference to quantitatively measure the similarity of the simulated preindustrial patterns to those derived from the GPCP dataset (Taylor 2001). As shown in Fig. 2, the CSIRO Mk3L-1.2, MIROC-ESM, BCC_CSM1.1, and FGOALS-g2 are inadequate to reproduce the spatial pattern of summer precipitation in East Asia, with correlation coefficients of less than 0.6 for at least two months and also for the JJA mean. In spite of the high spatial correlations of HadGEM2-CC and HadGEM2-ES for the June, August, and JJA mean, their standard deviations of the simulated patterns are larger than those of the reference. It indicates that the two climate models tend to exaggerate the amplitude of precipitation variation across regions. By contrast, the RMS difference provides integrated information about the simulated patterns. Among the remaining models, those with the JJA mean normalized centered RMS difference less than 0.85 are finally selected to analyze the EASM precipitation changes. The six selected models are the CCSM4, CNRM-CM5, FGOALS-s2, IPSL-CM5A-LR, MPI-ESM-P, and MRI-CGCM3. Compared with the

FIG. 1. Modern climatology of (a),(b) June, (c),(d) July, (e),(f) August, and (g),(h) JJA mean precipitation as derived from the (left) GPCP dataset for 1979–2008 and (right) CMIP5 preindustrial multimodel mean of six selected models.

observation, MMM of the six models could capture the seasonal marches of the EASM precipitation (Fig. 1). However, it underestimates the intensity of the maximum precipitation especially for the mei-yu season, which is

consistent with the smaller standard deviations shown in Fig. 2. Nevertheless, the MMM with the smallest RMS difference is still better than any individuals. Unless specifically stated, the following sections are based on the MMM results.

FIG. 2. Taylor diagram (Taylor 2001) for evaluating model (indicated by the numbers) performance in precipitation simulation compared to the GPCP dataset (reference). The radial distance from the origin indicates the standard deviation ratio of a model pattern relative to the corresponding reference; the azimuthal position indicates the correlation coefficient between the two patterns; and their normalized centered root-mean-square difference is proportional to the distance apart from the reference. Models finally selected for analysis are in green. MMM refers to the multimodel mean of these selected models.

4. Mid-Holocene precipitation changes relative to preindustrial

The different climate between the mid-Holocene and preindustrial mainly arises from the configuration of orbital parameters. The precession-dominated orbital forcing modifies the seasonal and latitudinal distribution of the incoming solar radiation (Fig. 3). Compared with the preindustrial, the boreal summer insolation increases during the mid-Holocene, with greater amplitudes at the high latitudes. It was well documented in previous studies that the mid-Holocene EASM intensified in response to insolation changes, as measured by the increased area-mean precipitation and the strengthened low-level meridional winds (Jiang et al. 2013; Zheng et al. 2013). The MMM JJA mean precipitation anomalies as shown in Fig. 4d further support the overall wetter pattern in monsoon-influenced East Asia (for results from each model, see Fig. S5). However, on the regional scale, there are considerable spatial disparities. In terms of the absolute changes in precipitation, positive anomalies occur in eastern China, with two maximum centers along the southwest–northeast direction and a weaker increase in between. If considering the preindustrial climatology, the relative increase of precipitation in inland northern China is remarkable

FIG. 3. Top of atmosphere insolation difference between the mid-Holocene (6 ka) and preindustrial period (0 ka), following the algorithm by Berger (1978).

and comparable to that in southern China. Areas with large relative changes are consistent with those characterized by high significance. In this study, significant changes mean the absolute value of MMM is larger than one standard deviation of the models. Except for the differences in magnitude, the summer mean precipitation decreases over west-central China (32° – 36° N, 100° – 106° E) and the northwestern Pacific (30° – 45° N, 125° – 145° E). The two negative anomalies roughly parallel to each other along the zonal direction, and the line between them intersects with the line that connects the significant positive anomalies in northern and southern China. On monthly scales, this cross-like pattern begins to develop in June and be stabilized during July and August (Figs. 4a–c), which is in response to a more pronounced insolation increase in the late summer (Fig. 3). For most parts of the EASM influenced regions (not including the subtropical North Pacific), the tendency of precipitation changes is accordant from June to August. Thus, the JJA mean results are used in the following analysis.

Except for east-central China (30° – 36° N, 110° – 120° E), the CMIP5-based precipitation changes are comparable to that derived from the KCM Holocene transient simulation (see Fig. 6 in Jin et al. 2014). Based on the empirical orthogonal function analysis, Jin et al. (2014) found relatively high JJA precipitation prevailing over northern and southern China during the early to mid-Holocene, which agrees with the significant precipitation increase as shown in Fig. 4d. By contrast, they found the deficit of precipitation between 30° and 40° N in East Asia, with significant signals located in west-central China, Japan, and the adjacent seas. These regions with significant decreases roughly overlap with those characterized by negative precipitation anomalies as presented in Fig. 4d.

FIG. 4. MMM anomalies (6 minus 0 ka) of (a) June, (b) July, (c) August, and (d) JJA mean precipitation. The stippled areas indicate where the absolute value of MMM is larger than one standard deviation of the models. Mid-Holocene moisture reconstructions are labeled in (d), with green for wetter and yellow for drier conditions relative to the present. Plus and minus signs mark the centers of positive and negative anomalies, respectively.

As shown in Fig. 4d, moisture reconstructions are unevenly spread in East Asia. The abundant lake records in the EASM northern marginal zone and the multiproxy records in southern China consistently point to a wetter mid-Holocene climate relative to the present, which agrees with the summer precipitation increase in the CMIP5 models. By contrast, few moisture reconstructions are available over northeastern China, the Korean peninsula, and Japan. The existing three records over these regions indicate a drier climate during the mid-Holocene and are consistent with the summer rainfall reduction in the models. The model-proxy discrepancy occurs in west-central China, where the MMM suggests an insignificant deficit in the precipitation while the peat and loess records indicate wetter conditions. These records are located on the eastern Tibetan Plateau (roughly around 33°N, 102°E) and its downstream Loess Plateau (36°N, 105°–110°E) with relatively high altitudes. Thus, both the orographic precipitation due to lifting of the moist air at the upwind slope of mountains and the precipitation forced by the southerly winds in the downstream of the Tibetan Plateau (Molnar et al. 2010; Chen and Bordoni 2014) compose important parts of the local water cycle. We

speculate that the limited spatial resolution and insufficient representation of topography in the climate models might be responsible for the underestimated precipitation and consequent model-data discrepancy (Gao et al. 2006, 2012). As shown in Fig. 1, the precipitation error is relatively large over regions with complicated topography. Moreover, the proxy uncertainty as presented in section 2 should also be noted. In addition to the local precipitation, other environmental factors such as the meltwater from the nearby mountains and river runoff might also be conducive to the moist conditions and play a role in amplifying the difference between model and proxy data.

5. Dynamic diagnostics of precipitation changes

a. Moisture budget

Figure 5 shows changes in the terms on the right-hand side of the moisture budget Eq. (3) from the preindustrial to the mid-Holocene. The results indicate that the vertical moisture advection $-\langle \omega \partial_p q \rangle$ is the dominant factor influencing the large-scale precipitation pattern in East Asia (Fig. 5b). The largest vertical moisture advection increases overlap with the largest precipitation

FIG. 5. MMM anomalies of the (a) vertical integral of horizontal moisture advection $-\langle \mathbf{V} \cdot \nabla q \rangle$, (b) vertical integral of vertical moisture advection $-\langle \omega \partial_p q \rangle$, (c) evaporation, and (d) residual term in the moisture budget. The stippled areas indicate where the absolute value of MMM is larger than one standard deviation of the models. Solid and dashed contours in (b) denote positive and negative precipitation anomalies, respectively, with an interval of 0.4 mm day^{-1} .

increases in coastal northern and southern China; in the meanwhile, negative advection corresponds to the reduced precipitation in west-central China, the Japan Sea, and its adjacent regions. Besides, the horizontal moisture advection $-\langle \mathbf{V} \cdot \nabla q \rangle$ plays a role in modulating precipitation on regional scales (Fig. 5a). In inland west-central China, the horizontal advection has an even greater impact on precipitation. However, changes in the horizontal moisture advection are largely offset by changes in the residual (Fig. 5d), that is these two terms appear to have the similar spatial pattern but with the opposite sign. As a result, their joint contribution to the precipitation is relatively small. The response of evaporation appears to be more uniform across regions, with increased evaporation on land in favor of excessive precipitation, and the opposite for the ocean (Fig. 5c). In terms of magnitude, the contribution from evaporation is negligible when compared with the others.

Following Eqs. (6) and (7), we found that changes in the moisture advection are primarily determined by circulation changes for continental East Asia (Fig. 6, left) and by specific humidity changes for the northwestern Pacific (Fig. 6, center). The covariation terms

are negligible for most parts of the monsoon-influenced regions (Fig. 6, right). In particular, the anomalous vertical motion dominates changes in the vertical moisture advection $-\langle \bar{\omega} \partial_p \bar{q} \rangle$ (Fig. 6g); therefore, it is also the key to explain the overall distribution of precipitation. As shown in Figs. 7i–l, the directions of vertical motion and its changes are nearly invariant with height. We select the vertical velocity at the midtroposphere (500-hPa level) to approximate the vertically integrated results. The spatial distribution of precipitation (Fig. 4d) well follows that of the 500-hPa vertical velocity (Fig. 8c), with the precipitation increases corresponding to the anomalous upward motions, and vice versa. In the subsequent section 5b, we use the MSE budget to further examine the physical processes associated with the anomalous vertical motion. On the regional scale, the deficit of precipitation in west-central China is mainly caused by the negative moisture advection due to anomalous zonal winds $-\langle \delta \bar{u} \partial_x \bar{q} \rangle$ (Fig. 6a). In eastern China, the considerable moisture advection increase due to meridional wind anomalies $-\langle \delta \bar{v} \partial_y \bar{q} \rangle$ is largely counteracted by changes in the meridional specific humidity gradient $-\langle \bar{v} \partial_y \delta \bar{q} \rangle$ and their covariance $-\langle \delta \bar{v} \partial_y \delta \bar{q} \rangle$.

FIG. 6. Contributions to the vertical integral of (a)–(c) zonal moisture advection anomalies, (d)–(f) meridional moisture advection anomalies, and (g)–(i) vertical moisture advection anomalies due to changes in (left) circulation, (center) specific humidity, and (right) their covariance. The stippled areas indicate where the absolute value of MMM is larger than one standard deviation of the models.

(Figs. 6d–f). Thus, the combined effect of horizontal moisture advection on precipitation is relatively small in eastern China (Fig. 5a).

b. MSE budget

In the framework of the MSE budget, the anomalous vertical motion is reflected by changes in the vertical MSE advection $-\langle\omega\partial_p h\rangle$. Given that the vertical integral of the MSE stratification $\partial_p h$ is negative in pressure coordinates, the negative value of ω , namely, ascending vertical motion, corresponds to the negative value of $-\langle\omega\partial_p h\rangle$, and vice versa. As shown in Fig. 8c, the anomalous ascending motion at the 500-hPa level overlaps with the decrease of $-\langle\omega\partial_p h\rangle$. The latter, in turn, is associated with the increase of the net energy flux $\overline{F^{\text{net}}}$, the moist enthalpy advection $-\langle\mathbf{V}\cdot\nabla m_E\rangle$, and residual δ_E in the MSE budget. As presented in section 5a, the anomalous vertical motion is the key factor influencing the large-scale precipitation patterns in East Asia. The combination of the moisture and the MSE

budget allow us to relate precipitation to local radiative forcing $\overline{F^{\text{net}}}$ and remote energy advection $-\langle\mathbf{V}\cdot\nabla m_E\rangle$. Note that the residual shown in Fig. 8d mostly plays a counteractive effect on vertical motion, thus be excluded from the following discussion.

1) LOCAL RADIATIVE FORCING

Relative to the preindustrial, the mid-Holocene net energy flux increases in continental East Asia and decreases over the northwestern Pacific (Fig. 8a), which contributes to the upward motions and precipitation increase in northern and southern China and the downward motions and precipitation decrease over the Japan Sea. In addition to the land–sea difference, the net energy increase is larger in southern China than that in northern China, which is consistent with the larger precipitation increase at the lower latitudes. To better understand the regional characteristics of energy distribution, we divide the EASM domain into three parts. They roughly represent northern China (NC; 35°–50°N,

FIG. 7. Pressure–latitude cross section of the MMM anomalies (color shading) of the (a)–(d) zonal wind u , (e)–(h) meridional wind v , and (i)–(l) vertical velocity ω (positive denotes downward motion) along 105°, 115°, 125°, and 135°E. The stippled areas indicate where the absolute value of MMM is larger than one standard deviation of the models. Solid and dashed contours denote the corresponding MMM preindustrial positive and negative values with an interval of 4 m s^{-1} , 1 m s^{-1} , and $0.5 \times 10^{-2} \text{ Pa s}^{-1}$ for u , v , and ω , respectively.

100°–120°E, note that this subregion also contains parts of Mongolia), southern China (SC; 20°–35°N, 100°–120°E), and the northwestern Pacific (NWP; 35°–50°N, 130°–150°E), respectively. In particular, within the given rectangles, we only consider the continental parts for the first two subregions, and the oceanic parts for the last one.

The area-weighted mean changes in energy flux are shown in Fig. 9. The incoming shortwave radiation at top of the atmosphere $S_t^\uparrow$ significantly increases over the three subregions in response to the precession-dominated orbital forcing. To maintain the equilibrium, most of the increased shortwave radiations are either reflected into

space $S_t^\uparrow$ or absorbed by Earth $S_s^\downarrow$, and only small parts of them back into the atmosphere from the surface $S_s^\uparrow$. For the northern regions including NC and NWP, more shortwave radiations are absorbed by the surface than those backed into space, while the opposite holds for the south (SC). We speculate that this relates to the heavier precipitation in southern China (Fig. 4d) where the cloud cover tends to enhance shortwave reflection and prevent it from reaching the ground. The north–south difference is also manifested in changes in the longwave radiation. In the northern regions, the increase of longwave radiation into space $L_t^\uparrow$ and into the surface $L_s^\downarrow$ leads to a decrease of net longwave radiation in the

FIG. 8. MMM anomalies of the (a) net energy flux into the atmospheric column F^{net} , (b) vertical integral of horizontal moist enthalpy advection $-\langle \mathbf{V} \cdot \nabla m_E \rangle$, (c) vertical integral of vertical moist static energy (MSE) advection $-\langle \omega \partial_p h \rangle$, and (d) residual term in the MSE budget. The stippled areas indicate where the absolute value of MMM is larger than one standard deviation of the models. Rectangles in (a) indicate the range of three subregions used in Fig. 9. Solid and dashed contours in (c) denote anomalous downward and upward 500-hPa vertical velocity, respectively, with an interval of $0.4 \times 10^{-2} \text{ Pa s}^{-1}$.

atmosphere, which could be explained by the widespread atmospheric warming (Figs. 10a–d). In southern China, the net longwave radiation increases as a result of the decrease of outgoing longwave radiation $L_t^\uparrow$, which is possibly associated with the stronger convective activities during the mid-Holocene. The sum of sensible heat $\text{SH}^\uparrow$ and latent heat $\text{LH}^\uparrow$ increases over continental East Asia, but decreases over the ocean. Changes in the latent heat satisfy the evaporation distribution as shown in Fig. 5c, and contribute most to the contrary net energy flux changes between land and sea. The above results indicate that although the incoming solar radiation is the driving factor for the mid-Holocene and preindustrial difference, the interaction of radiation and convection within the climate system plays a more important role in shaping the net energy flux distribution.

2) REMOTE ENERGY ADVECTION

For most parts of East Asia, changes in the horizontal moist enthalpy advection are much larger than those in the net energy flux but substantially offset by the opposite changes in residual (Fig. 8). Nevertheless, the

uneven distribution of $-\langle \mathbf{V} \cdot \nabla m_E \rangle$ is vital for the formation of the cross-like precipitation pattern. On the regional scale, the positive anomalies of $-\langle \mathbf{V} \cdot \nabla m_E \rangle$ roughly overlap with the ascending motions and the increase of precipitation, and vice versa. In northern and southern China, the positive anomalies of $-\langle \mathbf{V} \cdot \nabla m_E \rangle$ together with the net energy flux increase contribute to the prevailing ascending motions. By contrast, in west-central China, the Korean peninsula, and southern Japan, the anomalous descending motions are predominated by the negative anomalies of $-\langle \mathbf{V} \cdot \nabla m_E \rangle$, as the positive anomalies of $-\langle \omega \partial_p h \rangle$ can be explained neither by the net energy flux nor by the residual term. The moist enthalpy advection consists of two parts. They are the temperature-dominated dry enthalpy advection $-\langle \mathbf{V} \cdot \nabla (c_p T) \rangle$ and the moisture-dominated latent energy advection $-\langle \mathbf{V} \cdot \nabla (L_v q) \rangle$. We further decompose these advection terms and discuss the physical processes responsible for advection changes in northern China, west-central China, the northwestern Pacific, and southern China as follows.

The significant positive anomalies of $-\langle \mathbf{V} \cdot \nabla m_E \rangle$ are found in continental East Asia between 40° and 50°N

FIG. 9. Contributions to the area-weighted mean net energy flux anomalies $\overline{F}_{\text{net}}$ from changes in the shortwave (S), longwave (L) radiation, and the sensible heat (SH) and latent heat (LH) in northern China (NC, 35°–50°N, 100°–120°E), the northwestern Pacific (NWP, 35°–50°N, 130°–150°E), and southern China (SC, 20°–35°N, 100°–120°E). Note that only the continental parts within the first two rectangles are calculated, and only the oceanic parts within the last one are calculated. The subscripts t and s denote top of atmosphere and surface, respectively. Arrows indicate the positive direction. The vertical bars show the range of MMM plus or minus one standard deviation.

(Fig. 8b). The inland parts of the positive anomalies (excluding northeast Asia) are mainly sustained by the warm advection due to changes in the meridional winds $-c_p \langle \delta \bar{v} \partial_y \bar{T} \rangle$ (Fig. 11d). During the mid-Holocene, the increased insolation drives the enhanced land–sea thermal contrast, with the anomalous southerly winds prevailing over continental eastern Asia (Figs. 7e,f). The southerly winds bring warm air from the lower latitudes to higher latitudes, which is conducive to the positive anomalies of $-\langle \mathbf{V} \cdot \nabla m_E \rangle$. In particular, under the climatological mean state, the midlatitude baroclinic atmosphere features a substantial meridional temperature gradient, while the latitudinal thermal distribution is more uniform in the subtropical regions (Figs. 10i,j). As a result, the meridional wind–induced warm advection concentrates between 30° and 50°N. The anomalous southerly winds are also carriers of water vapor, and the related meridional moisture advection $-L_v \langle \delta \bar{v} \partial_y \bar{q} \rangle$ further contributes to the positive moist enthalpy advection anomalies through the latent heat release (Fig. 11j). In addition to the meridional winds, changes in the meridional temperature gradient play a second role in amplifying the warm advection in northern China. As shown in Fig. 3, the increase of insolation is unevenly distributed in the latitudinal direction, which finally results in the decrease of the meridional temperature gradient, especially for the middle latitudes (Figs. 10i–l). In continental East Asia, the climatological mean northerly winds incur cold advection in the mid–high troposphere (Figs. 7e,f). Thus, the decreased meridional temperature gradient acts to weaken the inherent cold advection and induce warm advection anomalies $-c_p \langle \bar{v} \delta \partial_y \bar{T} \rangle$ (Fig. 11e).

According to the thermal wind relationship, the weakened meridional temperature gradient closely relates to the easterlies anomalies (Figs. 7a–d). Such anomalies induce cold advection $-c_p \langle \delta \bar{u} \partial_x \bar{T} \rangle$ between 30° and 40°N in East Asia (Fig. 11a), where the climatological mean temperature tends to decrease from west to east in the troposphere (Figs. 10e,f). In west-central China, the climatological mean specific humidity increases from west to east near the surface, but decreases from west to east above the 800-hPa level (Fig. 12e). Given that the easterly anomalies are stronger at the upper troposphere (Fig. 7a), the vertical integral of the zonal moisture advection $-L_v \langle \delta \bar{u} \partial_x \bar{q} \rangle$ is dominated by negative anomalies (Fig. 11g). The relevant latent heat reduction combined with the cold advection accounts for the decreased moist enthalpy advection in west-central China (Fig. 8b).

Changes in the thermodynamic component rather than the circulation component play a leading role in modulating the moist enthalpy advection in the northwestern Pacific and northeastern Asia (Fig. 11). As mentioned above, the enhanced land–sea thermal contrast results in the prevailing negative zonal temperature gradient anomalies along coastal East Asia (Figs. 10g,h). The temperature changes further influence the specific humidity distribution, and the zonal specific humidity gradient also features negative anomalies during the mid-Holocene (Figs. 12g,h). Under the influence of the background westerlies (Figs. 7c,d), the negative zonal gradient anomalies cause the warm advection $-c_p \langle \bar{u} \delta \partial_x \bar{T} \rangle$ and increased latent energy advection $-L_v \langle \bar{u} \delta \partial_x \bar{q} \rangle$ (Figs. 11b,h). In the latitudinal direction, the meridional temperature and specific humidity gradients are reduced in response to the uneven insolation changes (Figs. 10k,l and 12k,l). For the northwestern Pacific, the prevailing southerly winds dominate the troposphere in the climatological mean state (Figs. 7g,h). Thus, changes in the meridional gradients lead to cold advection $-c_p \langle \bar{v} \delta \partial_y \bar{T} \rangle$ and decreased latent energy advection $-L_v \langle \bar{v} \delta \partial_y \bar{q} \rangle$ (Figs. 11e,k). In particular, the center of the zonal and meridional changes is located north and south of 40°N, respectively, which are accordingly consistent with the distribution of positive and negative moist enthalpy advection anomalies (Fig. 8b).

In southern China, the contribution from temperature advection to changes in the moist enthalpy advection is tiny when compared with the moisture advection. The enhanced southerly winds in combination with the considerable meridional gradient of the climatological mean specific humidity (Fig. 12j) lead to the significant increase of moisture advection $-L_v \langle \delta \bar{v} \partial_y \bar{q} \rangle$ in the Yangtze River valley (Fig. 11j). However, the weakened meridional specific humidity gradient due to the latitudinal insolation

FIG. 10. Pressure–latitude cross section of the MMM anomalies (color shading) of the (a)–(d) air temperature T , and its (e)–(h) zonal gradient $\partial_x T$, and (i)–(l) meridional gradient $\partial_y T$ along 105° , 115° , 125° , and 135° E. The stippled areas indicate where the absolute value of MMM is larger than one standard deviation of the models. Solid and dashed contours denote the corresponding MMM preindustrial positive and negative values with an interval of 1°C , $0.3 \times 10^{-3}^\circ\text{C km}^{-1}$, and $0.3 \times 10^{-3}^\circ\text{C km}^{-1}$, respectively.

difference exerts the opposite effect (Figs. 11k,l). This explains why the total moist enthalpy advection changes are insignificant over the above regions. Besides, cyclonic anomalies over the Tibetan Plateau give rise to the low-level westerlies anomalies in southwestern China (Figs. 7a,b and 13c). The westerlies are beneficial to the zonal water vapor transport $-L_v \langle \delta \bar{u} \partial_x \bar{q} \rangle$ (Fig. 11g), and dominate the significant increase of moist enthalpy advection in situ (Fig. 8b).

In most regions influenced by the EASM, the vertical profiles of wind and temperature show either the quasi-barotropic structure or symmetry to the midtroposphere (Figs. 7 and 10). Thus, the combination of the preindustrial

and mid-Holocene minus preindustrial 500-hPa wind and temperature fields could roughly reflect the qualitative changes in the vertical integration of horizontal temperature advection. Given that the atmospheric water vapor concentrates in the lower troposphere, the 700-hPa wind and specific humidity fields are used to illustrate changes in the moisture advection. Figure 13 summarizes the decomposition analysis of the moist enthalpy advection $-\langle \mathbf{V} \cdot \nabla m_E \rangle$. The dynamic component primarily determines $-\langle \mathbf{V} \cdot \nabla m_E \rangle$ changes in continental East Asia. The southerly wind anomalies are conducive to the ascending motions in eastern China, while the easterly wind anomalies contribute to the descending motions in west-central

FIG. 11. Contributions to the vertical integral of (a)–(c) zonal dry enthalpy advection anomalies, (d)–(f) meridional dry enthalpy advection anomalies, (g)–(i) zonal latent energy advection anomalies, and (j)–(l) meridional latent energy advection anomalies due to changes in (left) circulation, (center) air temperature or specific humidity, and (right) their covariance. The stippled areas indicate where the absolute value of MMM is larger than one standard deviation of the models.

China. In the northwestern Pacific, the role of the thermodynamic component is more important. The weakened meridional temperature and specific humidity gradients are crucial to the descending motions in the Korean peninsula, southern Japan, and the marginal seas.

6. Summary and discussion

A great amount of observational and modeling studies reveal the inhomogeneous changes of the EASM precipitation during the Holocene (e.g., Jin et al. 2014;

Zhou et al. 2016; Lu et al. 2019). However, the relevant dynamic mechanisms remain unclear. In this paper, we provided a detailed diagnostic of the summer precipitation difference between the mid-Holocene and preindustrial by using the simulations from six selected CMIP5 models. These models are capable of reproducing the large-scale precipitation pattern in the monsoon-influenced regions. The multimodel mean shows that relative to the preindustrial, the mid-Holocene EASM precipitation anomalies are characterized by a cross-like structure. The significant precipitation increases appear

FIG. 12. As in Fig. 10, but for the specific humidity q . The contour intervals for q , $\partial_x q$, and $\partial_y q$ are 1 g kg^{-1} , $1 \times 10^{-3} \text{ g kg}^{-1} \text{ km}^{-1}$, and $1 \times 10^{-3} \text{ g kg}^{-1} \text{ km}^{-1}$, respectively.

in northern and southern China. For the regions between 30° and 40°N , precipitation decreases in inland west-central China, the Korean peninsula, Japan, and the adjacent seas. The precipitation pattern is highly consistent with changes in the vertical motion.

During the mid-Holocene, the boreal summer incoming solar radiation increases in response to the altered orbital parameters. In the context of the MSE budget, the increased insolation is the largest contributor to the net energy flux augment, and the latter directly induces the diabatic updrafts in northern and southern China. The unique presence of the Tibetan Plateau and the land–sea contrast in East Asia increase the zonal asymmetry of tropospheric warming and enhance the

background southerly winds. The southerly winds further facilitate anomalous upward motions through the increase of moist enthalpy advection. In particular, the temperature advection due to the southerly winds has a greater influence on the vertical motion in northern China, while the moisture advection is more important for southern China. This could be explained by the climatological mean distribution of the meridional temperature and specific humidity gradients. It is worth noting that changes in the mean advection are largely offset by the residual term dominated by transient eddies. However, the available monthly outputs from the CMIP5 models are too coarse to resolve the transient eddies. Multimodel datasets with finer temporal

FIG. 13. Composite map of the MMM (a) preindustrial air temperature (color shading) and anomalies of horizontal wind (arrow) at the 500-hPa level; (b) preindustrial horizontal wind (arrow) and anomalies of air temperature (color shading) at the 500-hPa level; (c) preindustrial specific humidity (color shading) and anomalies of horizontal wind (arrow) at the 700-hPa level; and (d) preindustrial horizontal wind (arrow) and anomalies of specific humidity (color shading) at the 700-hPa level. The stippled areas indicate where the absolute value of MMM anomalies is larger than one standard deviation of the models. Plus and minus signs mark the predominant positive and negative anomalies of the vertical integral of horizontal temperature or moisture advection as shown in Fig. 11.

resolutions are expected to precisely diagnose the effect of transient eddies.

Another feature of the mid-Holocene insolation change is the larger increase at the high latitudes, but its effect on precipitation remains unclear in previous studies. Here we found the reduced pole–equator temperature and specific humidity gradients due to the latitudinal insolation difference are the main reasons for the anomalous descending motions and reduced precipitation in the Korean peninsula, southern Japan, and its adjacent seas. According to the thermal wind relationship, the reduced meridional temperature gradient corresponds to the weakening of westerlies. The consequent easterly anomalies are responsible for the suppressed upward motions in west-central China. It is suggested by Sampe and Xie (2010) that the ascending motion due to the warm advection by the westerlies is crucial in sustaining the mei-yu–baiu rainfall band from

central China to Japan. Our results confirm this from the opposite aspect that the easterly anomalies inhibit the ascending motion by triggering cold advection, especially for the near downstream of the Tibetan Plateau with large zonal asymmetry in temperature. However, the dry thermodynamic equation used in Sampe and Xie (2010) does not take the water vapor's effect into consideration. Following the MSE budget diagnostic in Chen and Bordoni (2014), we showed that changes in the moisture advection due to the weakening of westerlies contribute more to the downward motion anomalies in west-central China than the temperature advection. As shown in Figs. 7a–d, the negative westerly anomalies are skewed to the south of the preindustrial wind speed maximum, which indicates the northward shift of the westerly jet. Kong et al. (2017) argued that this northward shift is associated with a shortened mei-yu and prolonged midsummer rainfall stage during the

mid-Holocene. The increased summer precipitation in northern China simulated by the CMIP5 models is consistent with the prolonged midsummer rainfall season. For the downstream Yangtze River valley, the MMM results point to an increase in summer precipitation, which seems inconsistent with the shortening of the mei-yu season. According to our analysis, although the weakened westerlies play a role in suppressing precipitation, ultimately the precipitation increase is determined by the upward motion anomalies associated with the excessive net energy flux into the atmosphere and the latent heat release from enhanced southerly winds. Nevertheless, we want to highlight that the MMM increase is insignificant, and the precipitation change in the downstream Yangtze River valley from the mid-Holocene toward the present remains unresolved. To answer this question, more effort should be put on the sources of the intermodel discrepancy, and identifying the key processes through which the current climate model could be improved.

Furthermore, our results based on the CMIP5 equilibrium experiments partly agree with the KCM transient simulation, in which the summer precipitation in northern and southern China decreases from the early to mid-Holocene toward the present, while a contrary trend is found between 30° and 40°N in East Asia (Jin et al. 2014). Model–data comparison suggests that the simulated precipitation increase in northern and southern China agrees with the overall wetter conditions evidenced by the multiproxy records. The existing moisture reconstructions in northeastern China and Japan also support the decreased precipitation pattern nearby. By contrast, there is large uncertainty in west-central China, where the mean amplitude of precipitation changes is insignificant across models, and the decreasing trend does not conform to the moist condition indicated by the loess and peat records. Given the complicated topography over these regions, the horizontal and vertical resolution of climate models might be important factors constraining the precipitation intensity. How the models' resolution and other possible factors attribute to the above inconsistency remains to be solved in the coming studies.

Reconstruction studies of the Holocene EASM have often focused on its relationship to insolation changes at certain latitudes (e.g., Dykoski et al. 2005; Zhang et al. 2011; Stebich et al. 2015). From the difference between the mid-Holocene and preindustrial, we showed that the local insolation could only explain the precipitation changes in part of the monsoon-influenced regions including northern and southern China. As for the northwestern Pacific and the surrounding continents, in spite of the increased insolation, both model simulations

and proxy records yield a weakening of the precipitation during the mid-Holocene. The latitudinal uneven increase of insolation is considered as the main forcing for the weakening. On account of the contrary effect of local insolation and latitudinal insolation gradient on precipitation, their combination is conducive to a comprehensive understanding of the Holocene EASM.

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APPENDIX

Different Forms of the Moisture Budget

The moisture budget equation used in this study is in the advection form, which could be converted into the flux form as widely used in other studies (e.g., Chen and Bordoni 2014, 2016).

With the aid of the chain rule of differentiation, the horizontal and vertical advection terms in Eq. (2) can be written as

$$\begin{aligned}\mathbf{V} \cdot \nabla q &= u \frac{\partial q}{\partial x} + v \frac{\partial q}{\partial y} = \frac{\partial(uq)}{\partial x} + \frac{\partial(vq)}{\partial y} - q \frac{\partial u}{\partial x} - q \frac{\partial v}{\partial y} \\ &= \nabla \cdot (\mathbf{V}q) - q(\nabla \cdot \mathbf{V}),\end{aligned}\quad (\text{A1})$$

and

$$\omega \partial_p q = \omega \frac{\partial q}{\partial p} = \frac{\partial(\omega q)}{\partial p} - q \frac{\partial \omega}{\partial p} = \partial_p(\omega q) - q \partial_p \omega. \quad (\text{A2})$$

According to the equation of continuity

$$\nabla \cdot \mathbf{V} + \partial_p \omega = 0, \quad (\text{A3})$$

and the sum of $q(\nabla \cdot \mathbf{V})$ and $q \partial_p \omega$ equals zero. Thus, we take Eqs. (A1) and (A2) into Eq. (2) to derive

$$\langle \partial_t q \rangle + \langle \nabla \cdot (\mathbf{V}q) \rangle + \langle \partial_p(\omega q) \rangle = E - P. \quad (\text{A4})$$

If time averaging Eq. (A4), we will get Eq. (1) in Chen and Bordoni (2016) as shown below:

$$\langle \partial_t \bar{q} \rangle + \langle \bar{\nabla} \cdot (\bar{\mathbf{V}} \bar{q}) \rangle + \langle \partial_p (\omega \bar{q}) \rangle = \bar{E} - \bar{P}. \quad (\text{A5})$$

In Chen and Bordonì (2016), they ignored water vapor storage in the atmosphere (assuming $\langle \partial_t \bar{q} \rangle = 0$) and vertical velocity at the surface (assuming $\langle \partial_p (\omega \bar{q}) \rangle = \omega_s q_s = 0$); thus, Eq. (A5) can be written as

$$\bar{P} - \bar{E} = -\langle \bar{\nabla} \cdot (\bar{\mathbf{V}} \bar{q}) \rangle. \quad (\text{A6})$$

These assumptions are applicable to most of the regions influenced by the EASM; however, errors are large in regions with complicated topography such as the eastern Tibetan Plateau where the surface term cannot be ignored (Seager and Henderson 2013).

In this study, we use the advection form of the moisture budget to avoid the calculation of surface terms. Besides, decomposition of the vertical advection directly links precipitation changes to the anomalous vertical motion, which is the prerequisite of using the MSE budget to further examine the role of local radiation and moist enthalpy advection on precipitation.

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